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Expanding carbon neutrality strategies: Incorporating out-of-boundary emissions in city-level frameworks

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**Key Parameter**

**GDP**

**Socioeconomic Parameter**

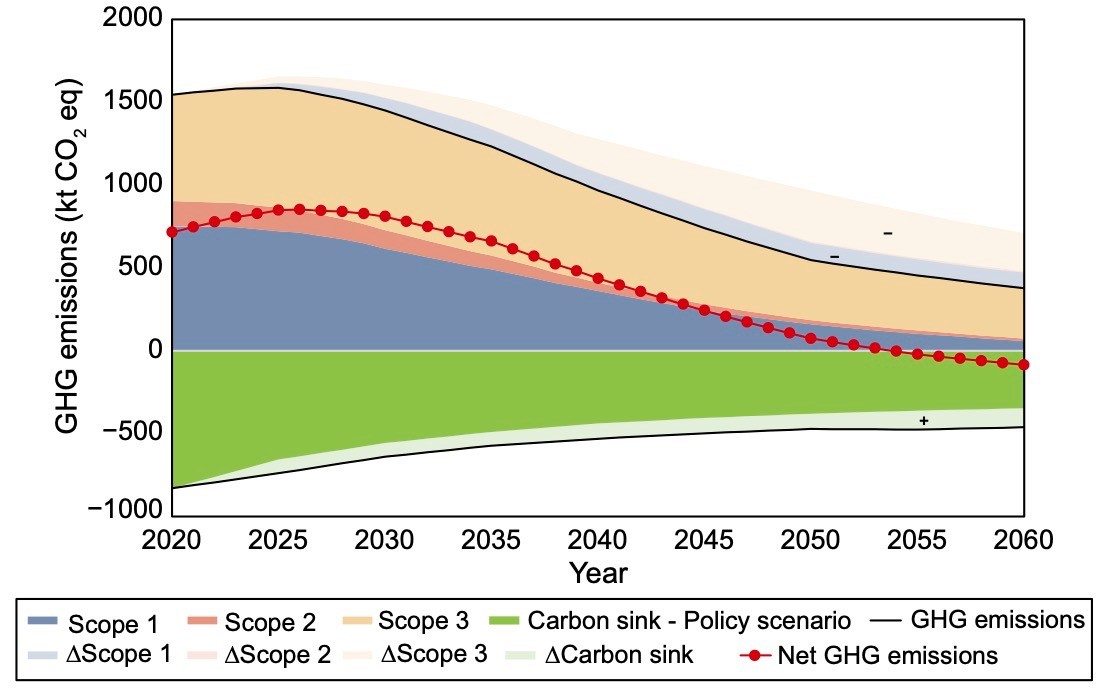
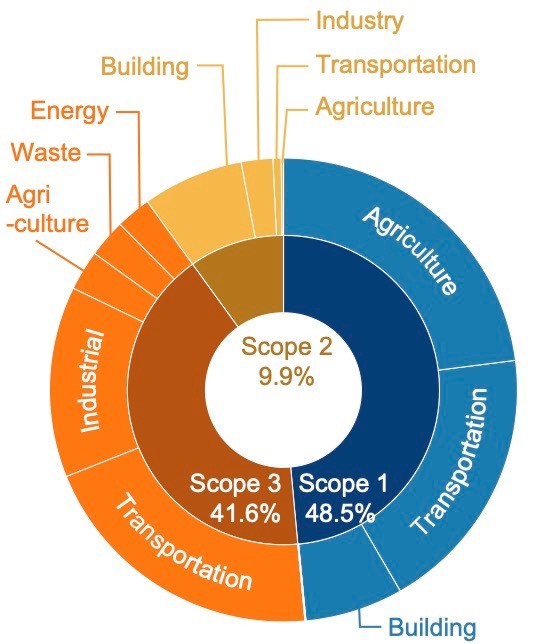
|  |  |
| --- | --- |
| **Energy Consumption** | |
|  |  |
| **Demand** | |

**Population**

**Emission Accounting**

**Pathway Projection**

|  |  |  |  |
| --- | --- | --- | --- |
| **Emission Characteristics** | **Policy Assumption** | **Renewable Energy Potential** | **Forest Sink** |



**CAEP-CP Model**

**Climate Goals Accessibility**

**Wuyishan Full-scope Carbon Neutrality Pathway**

1 Expanding Carbon Neutrality Strategies:

2 Incorporating Out-of-Boundary Emissions in

3 City-Level Frameworks

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1. ABSTRACT: Cities are increasingly vital in global carbon mitigation efforts, yet few have
2. specifically tailored carbon neutrality pathways. Furthermore, out-of-boundary indirect
3. greenhouse gas (GHG) emissions, aside from those related to electricity and heat imports,
4. are often overlooked in existing pathways, despite their significance in comprehensive
5. carbon mitigation strategies. Addressing this gap, here we introduce an integrated analysis
6. framework focusing on both production and consumption-related GHG emissions. Applied
7. to Wuyishan, a service-oriented city in Southern China, this framework provides a holistic
8. view of a city's carbon neutrality pathway, from a full-scope GHG emission perspective.
9. The findings reveal the equal importance of carbon reduction within and outside the city’s
10. boundaries, with out-of-boundary emissions accounting for 42% of Wuyishan's present
11. total GHG emissions. This insight highlights the necessity of including these external
12. factors in GHG accounting and mitigation strategy development. This framework serves
13. as a practical tool for cities, particularly in developing countries, to craft effective carbon
14. neutrality roadmaps that encompass the full spectrum of GHG emissions.

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1. KEYWORDS: greenhouse gas emissions, full-scope emission accounting, carbon
2. neutrality pathway, city-level

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## 1. INTRODUCTION

1. The rapid acceleration of global climate warming, which has pushed temperatures 1.2
2. °C above 1850–1900 levels [1] exacerbated the urgency [2] of achieving the Paris
3. Agreement targets, which is to keep warming to well below 2 °C and strive for a target of
4. 1.5 °C [3]. As the world’s largest energy consumer and carbon emitter [4], China
5. announced ambitious targets to reach a carbon peak by 2030 and carbon neutrality by 2060
6. [5]. This commitment is expected to lower global warming projections by around 0.2–0.3
7. °C [6]. To implement national strategies, China established a “1+N” policy framework to
8. decompose industrial and sub-national participation [7]. As sub-national actors, cities are
9. the primary units in China’s administrative system that formulate and implement measures
10. [8], creating a promising opportunity to assist mitigation efforts [9]. On the other hand,
11. pursuing carbon neutrality will help cities upgrade low-carbon technologies and cultivate
12. a sustainably developed industrial chain. As China’s urbanization advances, the net-zero
13. emission transition of cities becomes a key to achieving carbon neutrality in the country.
14. Promoting and implementing cities’ carbon neutrality commitments require a
15. concrete and feasible roadmap to guide governments [10]. Over 10,000 cities worldwide
16. have committed to climate mitigation, adaptation, and financing actions [11]. Furthermore,
17. 235 cities have proposed carbon neutrality [12]. To regulate and monitor these
18. commitments, several voluntary transnational climate initiatives have been established [13-
19. 15]. However, many of those initiatives only require reports on commitments [16],
20. resulting in cities facing a dearth of technical support for devising localized strategies for
21. emissions reduction and detailed abatement measures [17]. The heterogeneity of national,
22. industrial, and urban responses to the environmental systems, for instance, the
23. differentiated accessibility of offsetting carbon emissions [18], results in the inability to
24. directly replicate global or national carbon abatement roadmaps on cities [16]. Therefore,
25. city-specific carbon-neutral pathways need to be developed based on local characteristics
26. of the economic structure, technological potential, and resource endowment (including
27. renewable energy resources and carbon removal potentials) [19].
28. For policymakers, achieving a comprehensive understanding of emission inventory
29. [20-24] and designing the city-level carbon emission pathway and control strategies [25]
30. hold equal importance. Yet, full-scope carbon emissions still lack concerns when pursuing
31. carbon-neutral cities [26]. According to the greenhouse gas (GHG) protocol, the sources
32. and boundaries for city-level GHG emission inventory include scope 1, scope 2, and scope
33. 3 emissions [27, 28] (Fig. 1) (detailed definitions in Supplementary Information). Scope 1
34. and scope 2 emissions are referred to as territorial or production-based GHG emissions and
35. are usually reported and supervised by municipal authorities. Full-scope emissions cover
36. territorial and out-of-boundary supply chain (scope 3) emissions, providing a more
37. comprehensive picture of urban emissions for deep decarbonization. While cities’
38. territorial emissions are well understood, the out-of-boundary emissions embodied in
39. consumption are not comprehensively reported in the accounting inventories [16]. A few
40. city-level studies [29-32] explored scope 3 emissions, yet they generally focused on the
41. status quo, lacking a systematic approach for policy design to comprehensively and
42. objectively assess future emission pathways. In addition, few international climate
43. initiatives require municipalities to make commitments to address out-of-boundary
44. emissions [16].
45. In the realm of urban environmental commitments, there is a conspicuous absence of
46. explicit reduction pledges related to consumption or supply chain factors at the city level.
47. Consequently, it has become increasingly important to establish comprehensive emission
48. neutrality pathways tailored specifically to cities. Most cities import electricity, fuels,
49. water, food, and construction materials for their basic supply systems [33]. Consequently,
50. consumption-based emissions account for a considerable carbon footprint, especially for
51. service-oriented cities. Policies that ignore consumption-based emissions may have the
52. opposite effect from the original intentions [34]; affluent service-oriented cities may
53. outsource emission-intensive industries to less developed regions, resulting in potential
54. carbon leakage by cross-border product transfers. In contrast, policies that deal with full-
55. scope emissions allow wealthier cities to subsidize emission reductions in nearby energy-
56. producing towns and ensure a leading demonstration [35]. Therefore, including out-of-
57. boundary emissions when evaluating a city’s emissions and planning its reduction
58. pathways is necessary.
59. To fill the gaps, we focus on the city-level full-scope emissions and establish an
60. integrated methodology of GHG emission accounting and reduction pathway design. To
61. be more detailed, we calculate a city’s full-scope emissions based on sub-sectoral modules
62. and life cycle assessments and propose future carbon neutrality pathways using the Chinese
63. Academy of Environmental Planning Carbon Pathways (CAEP-CP) model [36]. We chose
64. Wuyishan city as our case study, which is located in Fujian province, China (see Fig. S1).
65. Wuyishan city pledges to be a pilot city for carbon peak and carbon neutrality in China. It
66. is also a typically service-orientated city. With the continuous industry structure transition,
67. the proportion of the tertiary industry will further increase, suggesting the increasing
68. importance of analyzing carbon mitigation strategy in service-orientated cities. This
69. study’s methodology provides a portable precedent for other cities, especially in

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developing countries, in planning a carbon neutrality roadmap.

## 2. MATERIAL AND METHODS

1. This study framework that projected the full-scope carbon neutrality pathway in
2. Wuyishan city included three parts: emission accounting, pathway projection, and
3. uncertainty analysis (see Supplementary Fig. S2).

## 2.1. Emission accounting

1. In this paper, the hybrid analysis [37-39] method was used to calculate full-scope
2. GHG emissions for Wuyishan city. The hybrid analysis integrated the advantages of the
3. top-down model (emission inventory method) and the bottom-up model (process analysis
4. method), thereby unifying these two methods in the same analytical framework [40].
5. According to the Kyoto Protocol, GHGs mainly encompass six types, i.e., carbon dioxide
6. (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons, perfluorocarbons, and
7. sulfur hexafluoride. The contribution of varying GHGs to global warming was reflected by
8. global warming potential (GWP), which was finally expressed as carbon dioxide
9. equivalent (CO2eq).
10. Scope 1 emissions were determined following the Intergovernmental Panel on
11. Climate Change (IPCC) guidelines (2006) [41], including fossil fuel combustion, industrial
12. processes and product use, waste, agriculture, forestry, and other land uses (AFOLU).
13. Several city departments were involved in fossil fuel combustion, including energy,
14. industry, transportation, and building sectors, as classified according to the 2019
15. Refinement to the 2006 IPCC Guidelines for National GHG Inventory [42]. In this work,
16. industrial process emissions were not included in scope 1 emission estimation as all
17. industrial enterprises in Wuyishan city did not involve such processes. In addition, the
18. treatment of solid waste, domestic sewage, and industrial wastewater in Wuyishan city,
19. which was conducted outside the city, was incorporated into our scope 3 emission
20. calculations. Agriculture emissions comprised the various facets of agricultural activities,
21. including manure management, enteric fermentation, rice cultivation, and planting soils.
22. The specific emission factors of agricultural activities were modified to fit Wuyishan’s
23. local situation. AFOLU represented changes in GHG emissions associated with
24. agriculture, forestry, and other land use practices. Scope 2 emissions covered indirect GHG
25. emissions from imported electricity. Owing to regional variations in technical levels and
26. energy compositions, the grid emission factor (*EF*Grid) preferentially relied on the local grid
27. emission factor (Fujian provincial grid emission factor) [43]. Scope 3 emissions included
28. GHG emissions from the consumption of products purchased from outside the jurisdiction,
29. cross-border traffic, and waste disposal. Product consumption refers to the carbon
30. emissions from upstream production, processing, and transportation of products outside
31. the city boundaries (such as water, food, construction materials, fuel, and other consumer
32. goods). As the main sources of food-related emissions were water, grains, and meat [44],
33. the production far exceeded the consumption in Wuyishan city [45], and there were no
34. food-related emissions in scope 3. Cross-border transportation refers to emissions from
35. urban cross-border transportation, including long-distance vehicles (passenger and freight),
36. railway, marine, and aviation. It was generally calculated using the miles traveled method
37. [46], with GHG emissions equally divided between the departure and destination cities.
38. Lastly, waste emissions encompassed GHG emissions stemming from the landfill and
39. incineration treatment of municipal solid waste, domestic sewage treatment, and industrial
40. wastewater treatment.
41. GHG emissions of Wuyishan city were calculated as follows：

159 𝐺𝐻𝐺Total = 𝐺𝐻𝐺Scope1 + 𝐺𝐻𝐺Scope2 + 𝐺𝐻𝐺Scope3 = ∑ 𝐴𝐷𝑖,𝑗 × 𝐸𝐹𝑖,𝑗 （1）

1. where *ADi,j* represented the activity level (product or energy) of consumption *j* in scope
2. *i*; *EFi,j* represented the GHG emission factor for *j*; *i* represented scope 1, scope 2, or scope
3. 3.

## 2.2. Emission pathway projection

1. In the analysis of the carbon neutral pathway in Wuyishan, the future development
2. characteristics of Wuyishan city were considered to set basic socio-economic parameters.
3. The basic parameters, including population, economy, urbanization, and electricity
4. consumption, were projected according to government planning and existing literature (see
5. Table 1).
6. This study, employing the CAEP-CP model, took a comprehensive approach by
7. considering the socio-economic development and industrial development characteristics of
8. Wuyishan city. Furthermore, it aligned with the ambitious target of reaching a carbon
9. emission peak by 2030 in Fujian province, with Wuyishan city pioneering the province in
10. achieving the peak and neutralization (Fig. S2). This study investigated future emission
11. pathways of Wuyishan city under two scenarios with different levels of energy efficiency,
12. activity, energy structure, and resource endowment of future industries or sectors
13. (transportation, building, agriculture, industry, carbon sink, etc.). We first designed the
14. policy scenario that considered measures including accelerating the development of
15. renewable power, increasing the proportion of electric vehicles, and improving energy
16. efficiency and electrification of buildings. Additionally, more aggressive measures were
17. introduced under the low-carbon scenario, in which a faster development of renewable
18. power, a higher proportion of electric vehicles, and more prominent energy-saving
19. renovation and electrification of buildings were implemented. For scope 3 emissions, the
20. policy scenario only focused on measures on the demand side, while the low-carbon
21. scenario focused more on the consumption choices of residents, such as the government
22. and residents prioritizing the purchase and use of low-carbon products. In terms of forest
23. carbon sink, the policy scenario only considered the improvement of forest management.
24. However, the low-carbon scenario also considered the optimal restructuring of forest
25. structure.
26. To be detailed, the carbon emissions of each sector were determined by both the
27. activity level and the emission factor. Through the assumptions of emission reduction
28. measures, the activity level or emission factor of each sector could be predicted, thereby
29. allowing for the calculation of future carbon emissions in each sector.
30. For the energy sector, according to the requirements of the National Energy
31. Administration for the promotion of rooftop distributed photovoltaic projects in counties
32. and districts [49], the promotion of rooftop photovoltaics would be the main emission
33. reduction measure in Wuyishan city in the future. According to the potential calculation
34. based on the rooftop photovoltaic area, the total photovoltaic capacity of Wuyishan city
35. would be 337,600 kilowatts (Fig. S3b in the Supplemental Information). Correspondingly,
36. in the low-carbon scenario, we assumed that by 2025, 2035, and 2060, the installed
37. capacity of rooftop photovoltaics would reach 67,500 kilowatts, 242,000 kilowatts, and
38. 337,600 kilowatts, respectively.
39. For the industry sector, since the tea industry was dominant in scope 1 and scope 2
40. emissions, we referred to the 14th Five-Year Plan for the tea industry in Wuyishan city
41. [50]. We assumed that the tea yield would reach 24,000 tons, 27,000 tons, and 33,000 tons
42. in 2025, 2035, and 2060, respectively, and we derived scope 1 and scope 2 energy
43. consumption to calculate GHG emissions. For scope 3 emissions, it was assumed that the
44. carbon emission factor per product unit would drop by 5% every five years by purchasing
45. low-carbon products, and the demand for products was predicted based on population
46. forecast.
47. For the transportation sector, fuel consumption, mileage, and emissions were
48. projected by forecasting the proportion of local vehicles (including private cars, buses, and
49. light-duty trucks) that were electric vehicles and the substitution rate of sustainable aviation
50. fuel [51, 52]. In the low-carbon scenario, the proportion of electric vehicles in Wuyishan
51. city would reach 20%, 60%, and 100% in 2025, 2035, and 2060, respectively. For scope 3
52. emissions, according to the tourism industry development plan [47], the number of tourists
53. was predicted to reach 20 million, 33 million, and 65 million in 2025, 2035, and 2060,
54. respectively. Sources of tourists and travel methods adopted the ratio of 2020, that was, the
55. proportion of tourists in the province and tourists from outside the province was 6:4. For
56. tourists from outside the province, 54%, 42%, and 4% of trips used high-speed rail, road,
57. and air travel, respectively. For tourists in the province, 33%, 67%, and 0% of trips used
58. high-speed rail, road, and air travel, respectively. The mileage was the average distance
59. from Wuyishan city to the corresponding city or provincial capital city. The carbon
60. emission factors per unit distance for high-speed rail, road, and air travel were referenced
61. from the report of the Chinese Academy of Engineering [53]. By 2025, 2035, and 2060,
62. these factors were projected to decrease by 25%, 50%, and 80%, respectively, compared
63. to 2020. These reductions were used to calculate the cross-border transportation GHG
64. emissions.
65. For the agriculture sector, based on the “Implementation Plan for Agricultural and
66. Rural Emission Reduction and Carbon Sequestration” [54], which mentioned “optimizing
67. paddy field irrigation management to reduce methane emissions from paddy fields”, we
68. assumed a decrease in methane emissions per unit of rice field yield of 25%, 70%, and 92%
69. in 2025, 2035, and 2060, respectively, compared to 2020. The future changes in rice
70. production and fertilizer usage were determined based on the forecast of the first industry
71. gross domestic product (GDP) to project GHG emissions.
72. For the building sector, we referenced the requirements in the “Fujian Province’s
73. Special Plan for Urban and Rural Infrastructure Construction in the 14th Five-Year Plan”
74. [55] and “Fujian Province Construction Industry 14th Five-Year Development Plan” [56].
75. It was assumed that the electrification rate of new buildings would be 100% in 2025 and
76. the electrification rate of existing buildings would reach 95% in 2035 and 100% in 2045.
77. In this way, we obtained energy consumption per unit building area. Together with future
78. building area data according to population forecast, emissions of the construction sector
79. can be calculated.
80. For the waste sector, we referenced the requirements in the “Accelerating the
81. Establishment and Improvement of the Implementation Plan for a Green, Low-Carbon, and
82. Circular Development Economic System in Fujian Province” [57] and the “Fujian
83. Province’s Long-term Special Plan for Waste-to-Energy Incineration (2019–2030)” [58].
84. We assumed that the carbon emission factor of a unit waste disposal would be reduced by
85. 5% every five years, and the future waste generation was predicted by the population (per
86. capita waste generation remains unchanged), to obtain the GHG emission of waste
87. disposal.

## 2.3. Data Sources

1. Data used in this study were collected from three sources: yearbooks of statistics,
2. literature and documents, and government departmental survey data. Details could refer to
3. Supplementary Information Text. The emission factor of fossil energy combustion was
4. collected from the IPCC Guidelines for National Greenhouse Gas Inventories (2006) [41],
5. product emission factor data were from the China Products Carbon Footprint Factors
6. Database [59], and grid emission factors were derived from the Ministry of Ecology and
7. Environment [60]. The GWP values came from the IPCC Sixth Assessment Report [9].

## 2.4. Uncertainty analysis

1. The uncertainty of GHG emission accounting mainly came from applied activity data
2. and emission factors. By referring to the IPCC guidelines [41], we adopted the methods of
3. quantifying the uncertainty for activity level and emission factor to determine the
4. probability distributions using the Monte Carlo simulation method. Equation (1) was used
5. in the simulation process, and each parameter was simulated for 10,000 trials. The detailed

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process could be referred to in our previous study [61].

## 3. RESULTS

1. **3.1. Full-scope GHG emissions in Wuyishan city**
2. The full-scope GHG emissions in Wuyishan city were estimated as 1545.6 kt CO2eq
3. (90% confidence interval: 1386.6–1704.0 kt) in 2020, in which the non-CO2 emissions of
4. 300.1 kt CO2eq (19.4%). Our results reveal that out-of-boundary (scope 3) emissions had
5. nearly equal weight to territorial emissions (scopes 1 and 2). Specifically, scope 1, scope
6. 2, and scope 3 emissions contributed 48.5% (749.1 kt CO2eq), 9.9% (152.9 kt CO2eq), and
7. 41.6% (642.6 kt CO2eq) of total GHG emissions, respectively; the carbon sink in Wuyishan
8. city was estimated as high as 830.9 kt CO2eq, which offset 54% of full-scope emissions.
9. Figure 2 shows the detailed breakdown of emissions for each scope with the sectoral
10. contribution.
11. The sectoral emission contribution showed significant differences between territorial
12. and out-of-boundary emissions (detailed data refer to Table S1). For territorial emissions,
13. agriculture (39.5%) and transportation (33.1%) sectors were the primary sources, followed
14. by building (23.6%) and industry (3.8%) sectors. Notably, the emissions in the agricultural
15. sector (357.0 kt CO2eq) were generally contributed by non-CO2 GHG (84.1%). With a high
16. share of primary industries (5.7% higher than the national average), rice cultivation and
17. livestock breeding were well developed, resulting in high CH4 (172.3 kt CO2eq) and N2O
18. emissions (116.0 kt CO2eq). High emissions in the transportation sector (289.6 kt CO2eq)
19. were mainly due to private vehicle ownership and freight transportation, among which
20. passenger vehicles, light freight, and motorcycles together contributed 84.7%. The building
21. sector was the third largest source (212.8 kt CO2eq), in which scope 1 emissions (104.7 kt
22. CO2eq) were about the same as scope 2 emissions (108.1 kt CO2eq). The building sector
23. consumed 76.5% of the city’s total electricity consumption in 2020, making it the leading
24. contributor to total scope 2 emissions.
25. The pattern of scope 3 emissions was related to the urban economy and industry
26. structure [62], mainly from the use of upstream raw materials and downstream waste
27. disposal. Among the 642.6 kt CO2eq out-of-boundary emissions, transportation (49.0%)
28. and industry (32.0%) stood out as the two major contributors. In 2020, Wuyishan city,
29. owning one of the five national parks in the territory, welcomed a substantial influx of
30. tourists, totaling 10.79 million visitors. This surge in tourism put more requirements on
31. cross-border transportation, leading to 315.2 kt CO2eq emissions. For the industry sector,
32. Wuyishan city was featured in tea-making and bamboo (accounting for 55.5% of the
33. industrial profit [45]). Due to the relatively homogeneous industrial enterprises within the
34. city, most enterprises purchased raw materials from outside the city, such as packaging
35. materials for tea-making, resulting in 114.3kt CO2eq scope 3 emissions. Besides,
36. construction materials, such as cement and steel, used in the building under construction
37. contributed to 91.3 kt CO2eq. Other sectors, including energy, agriculture, and waste,
38. together account for 19.0% of scope 3 emissions due to urban energy and fuel import,
39. agricultural fertilizer use, and municipal solid waste disposal.
40. In terms of carbon removal, the substantial increase in forest coverage to 80.5% in
41. Wuyishan city in 2020 [45] yielded a carbon sink of 830.9 kt CO2eq. This carbon sink was
42. mainly brought by the forest biomass stock, accounting for 77.5% of the total carbon sink,
43. followed by the soil organic matter stock (15.7%) and the forest dead organic matter stock
44. (6.8%) (Fig. S3a).

## 3.2. Pathway toward carbon neutrality in Wuyishan city

1. To facilitate the comparison with existing studies, future GHG emission pathways
2. constructed based on territorial (scopes 1 and 2) and full-scope (scopes 1, 2, and 3)
3. perspectives in Wuyishan city are discussed separately. Generally, both net territorial and
4. full-scope GHG emission (considering carbon removal) pathways show similar trends for
5. policy and low-carbon scenarios, which gradually increase and peak before 2030, followed
6. by a continuous decrease (Fig. 3).
7. Major mitigation measures under the policy scenario drive Wuyishan to achieve net
8. zero territorial emissions around 2045, 15 years ahead of China’s national target (2060).
9. Specifically, net territorial GHG emissions are projected to peak around 2028 (259.7 kt
10. CO2eq) and then decrease markedly in the following decades, declining to −7.3 and −172.0
11. kt CO2eq in 2045 and 2060, respectively (Fig. 3a, Table S2a). Such reductions underscore
12. the effectiveness of GHG controls, particularly in the building and agriculture sectors. In
13. the building sector, measures including promoting electrification and enhancing energy
14. efficiency are projected to yield remarkable results, with sectoral GHG emission reductions
15. of 85.0% in 2045 and a staggering 93.7% by 2060 (Table S2a). Similarly, in the agriculture
16. sector, due to effective controls on rice cultivation and fertilizer use, non-CO2 GHG
17. emissions (i.e., CH4 and N2O) will fall to 143.2 kt CO2eq in 2045 (52.3% lower relative to
18. 2020 levels). As to carbon removal, given the relatively high forest coverage and mainly
19. mature tree species, the carbon sink will inevitably decline to 406.2 kt CO2eq in 2045,
20. compared with 830.9 kt CO2eq in 2020 (Table S2a). Despite the substantial reductions,
21. forest carbon sinks would still play a critical role in offsetting territorial GHG emissions
22. and achieving carbon neutrality.
23. When out-of-boundary emissions are considered, our results suggest that Wuyishan
24. city cannot achieve full scope neutrality under the policy scenario before 2060 (Fig. 3b).
25. Our estimates suggest that scope 3 emissions in Wuyishan will increase by 156.7 kt CO2eq
26. (24.4%) from 2020 to 2030, stabilize after 2030, and peak in 2035 (800.7 kt CO2eq), then
27. gradually decrease to 532.9 kt CO2eq in 2060 (Table S2a). Particularly, due to the expected
28. substantial increase in future tourism, the transportation sector would contribute to a 140.4
29. kt CO2eq increase in GHG emissions in 2035 compared to 2020. However, we anticipate
30. a downward trend after 2035, primarily due to nationwide initiatives, such as new vehicles
31. and the promotion of sustainable aviation fuel acceleration, which will reduce emissions
32. from residents traveling to Wuyishan from other regions. In contrast, with the development
33. of the tea industry, emissions from the industrial sector would continue to increase (by 44.9
34. kt CO2eq in 2060). This is largely attributed to the consumption of packaging materials.
35. Considering all these factors, net full-scope emissions in Wuyishan would peak around
36. 2029, but still, 46.8% (333.3 kt CO2eq) of the 2020 emissions would be emitted in 2060,
37. miles away from the net zero target (Fig. 3b).
38. Fortunately, additional consumption-based measures, enhanced forestry management,
39. and renewable energy generation would help Wuyishan city achieve full-scope GHG
40. neutrality before 2060. Under the low-carbon scenario, net full-scope emissions in
41. Wuyishan will peak in 2026 at 851.5 kt CO2eq (three years earlier than in the policy
42. scenario with an 18.9% lower peak level) and reduce to −86.3 kt CO2eq in 2060 (Figs. 3d
43. and 4a, Table S2b).
44. For territorial emissions, our model shows that Wuyishan city is one of the highest
45. resource origins in Fujian Province for annual solar radiation, which is conducive to
46. promoting the development and construction of distributed photovoltaic (PV) power plants
47. (Fig. S3b). With 163.9 megawatts of installed PV capacity in Wuyishan city expected by
48. 2030, 52.5 kt CO2eq is expected to be reduced per year, particularly in the building sector
49. (Fig. 4b). Besides, enhanced stringency on measures, including vehicle electrification
50. promotion (to 50% in the year 2030) and rice cultivation and fertilizer use controls, under
51. low-carbon scenario are expected to achieve additional 38.4 and 34.1 kt CO2eq GHG
52. mitigation benefits in the transportation and agriculture sectors, respectively, in 2030
53. compared to the policy scenario (Fig. 4b).
54. Furthermore, altering the tree species structure can effectively decelerate the decline
55. of carbon sink, ultimately resulting in increased carbon offsetting over the medium and
56. long term. This strategy emphasizes optimizing the tree species structure, involving
57. replacing mature trees with young saplings. The above measure will result in a short-term
58. decrease in carbon sinks brought by forest biomass stock, with no significant downward
59. advantage until 2030, which will be 6.0% lower than the policy scenario (−23.3 kt CO2eq).
60. However, in the long term, the carbon sink will stabilize after 2045 and reach 462.2 kt
61. CO2eq in 2060, 32.7% higher than the policy scenario (Fig. 4). Considering the mitigation
62. measures for territorial emissions and carbon sink in the low-carbon scenario, net territorial
63. emissions will neutralize around 2035 (about ten years earlier than in the policy scenario)
64. and fall to −389.0 CO2eq in 2060 (Fig. 3b).
65. For the considerable out-of-boundary emissions, a range of consumption-based
66. measures is available, which could be supported by the government of Wuyishan city to
67. achieve the full-scope neutrality goals (Fig. 4a). As Wuyishan city is still in continuous
68. economic growth, the urbanization process will continue to advance; tourism is on the rise,
69. and cross-border travel and transportation activities are becoming more frequent, leading
70. to the growing demand for passenger and freight transport. Passenger growth is the main
71. factor leading to the transportation scope 3 emission rise in a short period. But nationwide
72. full electrification penetration would accomplish an emission reduction of 145.7 kt CO2eq
73. in 2060 (Table S2). On the other side, due to the increasing consumption of building and
74. packaging materials from new construction, the industrial sector is the only sector
75. increasing scope 3 emissions after 2030 and will become the largest emitter (62.0%) in
76. scope 3 emissions by 2060. The low-carbon scenario encourages the use of lower-carbon
77. upstream raw materials for enterprises (including construction materials, such as cement
78. and steel, and other primary supplies) and the control of the entire industrial chain (such as
79. logistics transportation and product packaging brought by tea companies). As a result of
80. low-carbon upstream and downstream products and processes, the industrial sector would
81. reduce an additional 62.7 kt CO2eq emissions in 2060 compared to the policy scenario (Fig.
82. 4b). Compared to the policy scenario, the stronger measures under the low-carbon scenario
83. are expected to achieve the full-scope neutrality goal before 2060 in Wuyishan (Figs. 3d
84. and 4).

## 4. CONCLUSIONS and DISCUSSIONS

1. Cities are fundamental administrative units in China to implement low-carbon
2. policies. This paper establishes an integrated methodology to account for city-level full-
3. scope emissions and assess the city’s carbon peak and neutrality pathways with scope 3
4. emissions incorporated. The efficacy of this methodology is demonstrated through a case
5. study of Wuyishan city, a typical service-orientated city in China. Notably, scope 3
6. emissions constitute a significant portion (42%) of the city's overall emissions, highlighting
7. the importance of addressing both internal and external sources for carbon reduction. When
8. it comes to full-scope GHG emissions, Wuyishan city is poised to achieve substantial
9. mitigation by 2025, primarily through strategies such as PV installation, 100% industrial
10. electrification, transitioning to electric vehicles, and waste incineration (Fig. 5). By 2035,
11. the city is set to witness a rapid expansion of PV installed capacity to 242,000 kW, along
12. with a 60% electric vehicle adoption rate. Additionally, an electrification rate of 95% is
13. targeted for buildings. In the agriculture sector, efforts will focus on reducing chemical
14. fertilizers and improving rice water irrigation management. All sectors must undergo
15. further low-carbon transition to achieve full-scope carbon neutrality before 2060. The PV
16. installed capacity needs to reach the maximum potential of 337,600 kW. Furthermore, the
17. electric vehicle and electrification rates of new buildings should reach 100%. The industry
18. sector should actively engage in mitigation efforts by purchasing low-carbon products,
19. while the transportation sector should focus on reducing emissions by incorporating
20. sustainable aviation fuels. Additionally, the waste sector needs a 35% reduction in waste
21. proposal GHG intensity.
22. Our study attempts to investigate full-scope GHG accounting and carbon pathway
23. planning for a city, which aligns with the current policy needs. The Chinese government is
24. vigorously promoting the establishment of a unified and standardized carbon emission
25. statistics and accounting system, which includes the extended measurement of implicit and
26. consumption-based emissions [63]. Scope 3 emissions are traditionally neglected in the
27. city’s GHG accounting, thereby underestimating urban emissions. It is insufficient to paint
28. a complete picture of urban GHG emissions or support the development of a sustainable
29. and low-carbon society. Our study finds that Wuyishan’s scope 3 emissions are about the
30. same as scope 1 and scope 2 emissions. For other cities, scope 3 emissions far exceed their
31. territorial emissions [30]. As the carbon neutrality target advances, many cities are
32. gradually transitioning towards tertiary industries and becoming service-oriented, which in
33. turn increases the scope 3 emissions significantly [64]. Accounting scope 3 emissions
34. makes it possible to fair compare the carbon neutrality targets of net producer cities and
35. net consumer cities.
36. Noticeable territory emission reductions are brought about by measures in various
37. fields, including vigorous electrification processes, energy efficiency improvement, and
38. the development of renewable energy generation [25]. Common paths to becoming a
39. carbon-neutral city include energy-efficient buildings, zero-carbon transportation, striving
40. for 100% renewable energy, and reducing waste and water [65]. In our study, Wuyishan
41. city attributes more than half of the emission reductions to electrification and renewable
42. energy development. Offsetting residual emissions is also a significant way [66, 67]. Cities
43. often have limited coverage and geological resources, which curtail their capacity to extract
44. carbon from the atmosphere and safely sequester it on a land base. The role of other forms
45. of carbon sequestration and offsetting becomes even more critical. Using nature-based
46. solutions, such as restoration and management of native ecosystems, emerges as a viable
47. avenue for creating a stable carbon sink while simultaneously promoting enhanced
48. biodiversity — an imperative for sustainable development [68]. Consequently, this
49. approach stands as a priority for offsetting choice. Additionally, in most cities, sectors like
50. coal power, waste incineration, and cement industries play pivotal roles in adopting carbon
51. capture technologies, although not applicable to Wuyishan city with the limited scales of
52. these industries. By partnering with carbon sequestration sites, cities could invest in
53. establishing carbon capture and sequestration chains to facilitate the deployment of large-
54. scale removals, achieving win-win results.
55. However, those traditional reduction measures have little effect on scope 3 emissions.
56. Emission reduction measures on the consumption side differ from those on the production
57. side, focusing more on low-carbon consumption by public participation and emission
58. control covering the industry chain. Mitigation measures, such as using upstream and
59. downstream low-carbon products, raising public awareness, changing lifestyles, and
60. enhancing low-carbon consumption, can bring considerable scope 3 emission reduction
61. benefits. These benefits, often underestimated, should be actively promoted for the future.
62. Carbon neutrality cannot be realized through the sole efforts of the management
63. department in implementing regulatory policies; rather, it necessitates the active
64. participation of all stakeholders, including the public sector, private sector, and citizens
65. [69, 70]. New industrial and economic development opportunities are essential drivers of
66. those stakeholders. Since scope 3 emissions occur outside the administrative boundaries of
67. cities, broader coordination among higher levels of governance (e.g., regional, national,
68. international) is required for net-zero consumption emissions, especially for systems that
69. operate on a larger scale, such as the power grid [71]. Collaborative initiatives like the
70. Covenant of Mayors can provide a valuable platform for small-sized cities to engage in
71. collaboration across different levels of government [72, 73]. Consequently, a city’s net-
72. zero goal for full-scope GHG emission helps to extend its influence and drive the entire
73. region or other cities nearby to improve reduction ambitions.
74. With Wuyishan city being one of the first pilot cities to reach the emission peak, the
75. results of this study hold immense value, offering operational, replicable, and extensible
76. experiences and practices, especially for service-orientated cities. This research strongly
77. supports future research on implicit carbon emission accounting on the consumption side.
78. However, there are still some limitations in this study. Data uncertainty and sensitivity
79. significantly impact the carbon footprint estimation, especially for scope 3 emissions.
80. Consequently, there is a compelling need for further reduction of such uncertainties.
81. Moreover, the uncertainty inherent in the emission accounting process arises from factors
82. like activity levels and emission factors, which cannot be overlooked [41]. To tackle this
83. issue, we measure and control the uncertainty range by considering the vital parameters’
84. probability distribution through a Monte Carlo approach. In the pathway projection, the
85. policy scenario assumptions strongly depend on the city’s future development plans, thus
86. generating substantial uncertainty. In this study, local and provincial governments’ macro
87. plans are investigated in detail to keep the scenario construction firmly grounded in reality.
88. Future research can continue to reduce the uncertainty in emissions accounting and future
89. scenario construction and seek more robust transition pathways in the highly uncertain
90. future. Although future scenarios are constructed and simulated based on macro policies
91. rather than cost-based optimization analyses, the cost is a critical factor to be considered
92. when developing mitigation strategies, which should be incorporated when implementing
93. the measures. Even with these limitations, our results are expected to shed light on full-
94. scope emission accounting and future pathway planning for cities in China and other
95. countries.

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## 494 Supporting Information

495 The following Supporting Information is available free of charge. Data for GHG

496 emissions and emission pathways under different scenarios by scope and sector, and the

497 geographical location figure of Wuyishan city.

498

## CRediT authorship contribution statement

1. **Zhe Zhang:** Conceptualization, Methodology, Investigation, Data Curation, Visualization,
2. Writing - Original Draft. **Mingyu Li:** Investigation, Data Curation, Writing - Original
3. Draft. **Li Zhang:** Conceptualization, Investigation, Data Curation, Visualization, Writing
4. - Original Draft, Supervision. **Yunfeng Zhou:** Data Curation. **Shuying Zhu:**
5. Visualization. **Chen Lv:** Investigation. **Yixuan Zheng:** Investigation, Writing - Review &
6. Editing, Supervision. **Bofeng Cai:** Conceptualization, Investigation, Supervision. **Jinnan**
7. **Wang:** Conceptualization.

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## 508 Declaration of competing interest

509 The authors declare that they have no known competing financial interests or personal

510 relationships that could have appeared to influence the work reported in this paper.

511

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7. **Figure 1.** The system boundary of GHG emission accounts for scopes 1, 2, and 3.
8. **Figure 2.** Breakdown of GHG emissions by scope and sector. **a**, Relative contribution by
9. scopes and sectors. **b**, Estimated GHG emissions and sinks from different sources.
10. **Figure 3. a**, **c**, Net territorial GHG emissions covering scope 1, scope 2 emissions, and
11. carbon sink of emission project under the policy (**a**) and low-carbon (**c**) scenarios. **b**, **d,**
12. Net full-scope GHG emissions covering scope 1, scope 2, scope 3 emissions, and carbon
13. sink of emission project under the policy (**b**) and low-carbon (**b**) scenarios. The black and
14. grey full lines indicate the mean, and the shading shows the intervals of percentiles.
15. **Figure 4.** GHG emission pathway under low-carbon scenario and the difference between
16. the policy and low-carbon scenarios by scope (**a**) and sector (**b**). The minus sign (−)
17. represents the GHG emission reduction, and the plus sign (+) represents carbon sink
18. enhancement under the low-carbon scenario compared to the policy scenario.
19. **Figure 5.** Carbon neutrality roadmap for Wuyishan city in the short, medium, and long
20. term.

742

743 **Table 1. Socio-economic key parameters for future scenario projection**

**Year**

**Parameters**

## Reference

consumption (GWh)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **2020** | **2025** | **2030** | **2035** | **2040** | **2050** | **2060** |  |
| Population (thousand) 256.7 | 258.6 | 259.6 | 258.7 | 256.7 | 249.0 | 239.5 | [47] |
| GDP growth rate (%) 0.1 | 7 | 6.3 | 6.0 | 5.5 | 3.0 | 2.5 | [47] |
| Urbanization rate (%) 60 | 65 | 70 | 74 | 77 | 80 | 82 | [47] |
| Total social electricity 615 | 733 | 837 | 936 | 1033 | 1141 | 1200 | [48] |
| Per capita electricity 2395 | 2836 | 3226 | 3618 | 4024 | 4582 | 5009 | [48] |

consumption (kWh) 744

Scope 2 Scope 1 Scope 3

Net-imported electricity

Scope 3

Industrial process

Agriculture

Sewage disposal

Cross-border transportation

Raw material

Fossil fuel

Goods and services

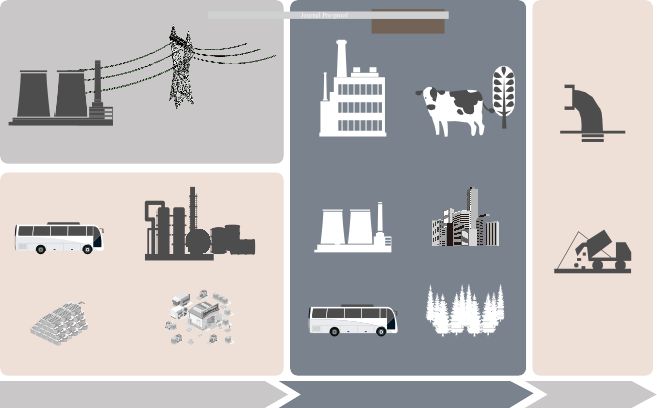
Industry

Transportation

Building

Forestry

Waste disposal

Upstream City boundary Downstream

**a**

Building Energy

Industry **b**

Transportation Agriculture

800

600

Waste Agri

-culture

Scope 2

9.9%

Scope 3 Scope 1

400

200

Carbon emission and carbon sink (kt CO2 eq)

0

−200

−400

−600

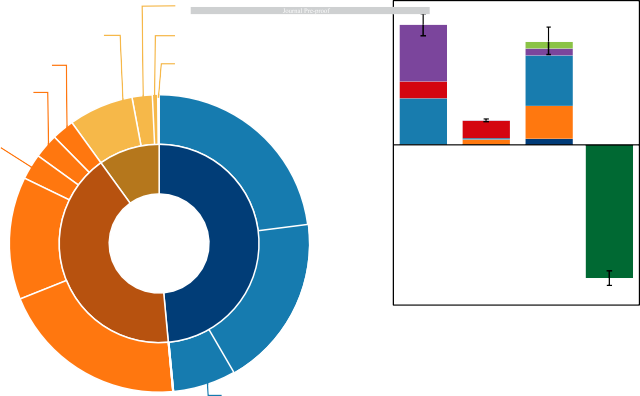
−800

41.6% 48.5%

u

Scope Scope Scope Carbon

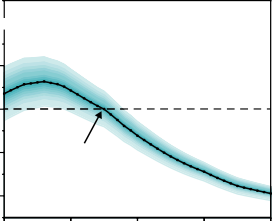
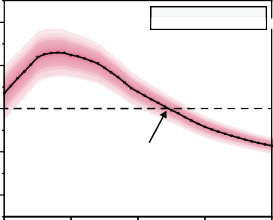
1 2 3 sink



Building

Energy Industry Transportation Building Agriculture Waste

**a**



Policy scenario **b**

Low-carbon scenario

Territorial neutrality

Territorial neutrality

400

Net territorial GHG emissions (kt CO2 eq)

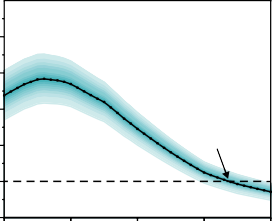
200

0

−200

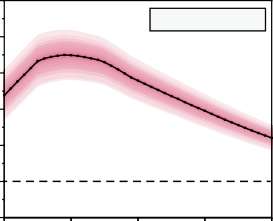
−400

**c** 1500 **d**



Full-scope neutrality

Low-carbon scenario



Policy scenario

Net full-scope GHG emissions (kt CO2 eq)

1200

900

600

300

0

−300

Year Year

Mean GHG emissions (kt CO2 eq)

Policy scenario Low-carbon scenario

95%

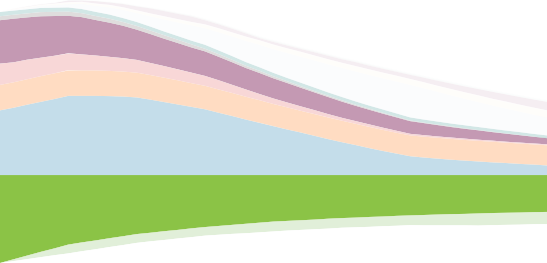
75%

50%

25%

5%

**a** 2000 **b** 2000



1500 1500

GHG emissions (kt CO2 eq)

GHG emissions (kt CO2 eq)

1000 1000

500 500

0 0

−500 −500

−1000

2020 2025 2030 2035 2040

2045 2050 2055 2060

−1000

2020 2025 2030 2035 2040 2045 2050 2055 2060

Year Year

Scope 1

∆Scope 1

Scope 2 Scope 3 Carbon sink - Policy scenario

GHG emissions

∆Scope 2 ∆Scope 3

∆Carbon sink

Net GHG emissions

Industry Energy Transportation Building Agriculture Waste

∆Industry ∆Energy ∆Transportation ∆Building ∆Agriculture ∆Waste

PV installed capacity of 67,500 kW

Energy

PV installed capacity of 242,000 kW

# 2060

PV installed capacity of 337,600 kW

2025 2035



100% electric

Industry

Purchase of low carbon products such as steel, cement and tea packaging materials

Electric vehicles reach 20%

Transpor

-tation

Electric vehicles reach 60%

Electric vehicles reach 100%; Sustainable aviation fuel mentions aviation kerosene

Energy-saving renovation of existing buildings, electrification rate reached 95%

Buildings

100% electrification rate of new buildings

Reduce the use of chemical fertilizers; increase the use of organic fertilizers

Agricult- ure

Implementation of rice water irrigation management, rice GHG emission intensity reduced by 70%

Rice GHG emission intensity reduced by 72%

Establishment of waste incineration plants

Waste

35% reduction in greenhouse gas emissions per unit of waste disposal



Highlights：

* We propose a framework to investigate the city-level carbon neutrality pathway.
* A full-scope GHG emission perspective is considered.
* Carbon reductions within and outside city’s boundaries are equally important.
* We suggest including out-of-boundary emissions in GHG accounting.



**Declaration of interests**

☐√ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

* The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: